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# Thermoeconomic and ecological analysis applied to heating industrial process in chemical reactors

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A B S T R A C T

In this work is presented the case that evaluates the possible environmental and economical gains with the application of water solar heating as an alternative for the consumption of natural gas in chemical reactors from cosmetic industries. The proposal consists of pre-heating of water for a boiler producing steam to heat several reactors from an industrial unit and measure the impacts caused by this application. It is used an analysis methodology based on thermoeconomic optimisation for a steam generation unit and production reactors heating in a chemical plant. This methodology consists at first in identifying the system functions as a whole and then individually for each unit, creating the thermoeconomic functional diagram, formulating the cost problem and solving the mathematical equations associated to the system. Based on the investment demands, expected results for fossil fuel consumption reduction and a consequently beneficial impact on the amount of greenhouse effect gases emission and a payback of approximately two years, this solution in study might be consider attractive.


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**Nomenclature**

| | |
|---|---|
| $c_{annual\text{-}ng}$ | natural gas annual cost [US$/year] |
| $c_{annual\text{-}ng2}$ | natural gas annual cost in scenario 2 [US$/year] |
| $c_{ng}$ | natural gas cost [US$/kW h] |
| $c_{ng2}$ | natural gas cost in scenario 2 [US$/kW h] |
| $c_{OMcb}$ | cost for conventional boiler operation and maintenance [US$/kW h] |
| $c_{OMcb2}$ | cost for conventional boiler operation and maintenance for scenario 2 [US$/kW h] |
| $c_{OMso}$ | cost for softening operation and maintenance [US $/kW h] |
| $c_{OMws}$ | cost for water softened operation and maintenance [US$/kW h] |
| $c_p$ | water specific heat [kJ/kg °C] |
| $c_s$ | steam cost [US$/kW h] |
| $c_{so}$ | softening water cost [US$/kW h] |
| $c_{so2}$ | softening water cost for scenario 2 [US$/kW h] |
| $e_{annual}$ | annual natural gas reduction [kW h/year] |
| $e_{annual\text{-}ng}$ | annual natural gas cost reduction [US$/year] |
| EPC | exergetic production cost [US$/kW h] |
| $f$ | annuity factor [year$^{-1}$] |
| $H$ | operation period for the system [h/year] |
| HHV | high heat value [kJ/kg] |
| $I_{cb}$ | conventional boiler investment [US$] |
| $I_{cb2}$ | conventional boiler investment for scenario 2 [US$] |
| $I_{so}$ | softening investment [US$] |
| $I_{so2}$ | softening investment for scenario 2 [US$] |
| $m$ | mass of water [kg] |
| $P$ | power installed [kW] |
| Q | energy amount [kJ/day] |
| $Q_{ng}$ | natural gas—annual consumption [kW h/year] |
| $Q_{ng2}$ | natural gas—annual consumption with solar heating [kW h/year] |
| $Q_{ng3}$ | natural gas—annual consumption with solar heating and economizer [kW h/year] |
| $R_{CO_2e}$ | greenhouse effect gases reduction [$t_{CO_2e}$] |
| $T_{in}$ | inlet temperature [°C] |
| $T_{out}$ | outlet temperature [°C] |

## 1. Introduction

The water heating technology through solar panels has been largely diffused and its use has experienced a moment of great expansion around worldwide. In Brazil, this recent expansion is directly associated to the electrical power cost increase during the last decade. This power source is commonly applied to water heating, especially for replacement of electrical showers use in the Brazilian houses. This expansion can be highlighted by the case of several Brazilian cities like Sao Paulo and Belo Horizonte, for example, which have sanctioned laws to incentivise the use of solar energy, both photo-thermal and photovoltaic.

However, other important possibilities are economical and environmental gains obtained by solar heating, such as reduction of greenhouse gases effect and its consequent impact into global warming that is not realised by the majority of common users, but can represent important opportunities for advance in the Brazilian balance of atmospheric emissions.

The water heating involves a great energy demand for its production and oil derivatives are used as fuel for heating systems, highlighting the use of natural gas for boilers. Nowadays, the natural gas offers clear economical and environmental advantages. There are great opportunities for cost reduction with the solar heating usage as an alternative for heating by electrical power; there are also significant opportunities for cost reductions with the application of this same renewable source, because reduction of fossil fuel consumption and greenhouse effect gases emission, especially the carbon dioxide. It can also be highlighted the opportunities represented by the possible use o solar energy for heating buildings sourced by natural gas as a contribution element against greenhouse effect gases emission.

Several works based on development of methodologies to model and to optimise thermal energy systems had been looked up to obtain information about techniques used in these evaluations [1–7].

Development of models for thermoeconomic design and operation optimisation had also evaluated. These works appoints to thermoeconomic optimisation and the best way to obtain the balance between exergy balance and energy production/generation costs [8–15].

Thermoeconomics had been explained through several works that relate exergy balance analysis and costs minimisation. This literature was important to materialise basic fundamentals that are very important to develop the proposed methodology [16–24].

Photovoltaic applications associated to solar water heating into rural zones, residences, commerce, and industries have been studied by several authors highlighting optimal performance of solar panel [25–32], also hybrid systems with other renewable sources such as hydrogen and biogas [33], photovoltaic panel control [34], and design optimization have been studied [35–38].

Some authors have developed works about modelling and measurement of greenhouse gases (GHG) emissions, i.e., based on trigeneration systems for cooling, heating and electricity purposes [39] and on carbon dioxide emissions matrix due to an increase of electricity demand in buildings as well as solid and liquid wastes treatment [40].

The Intergovernmental Panel on Climate Change (IPCC) has a methodology to estimate the methane emissions called IPCC protocol, which had been studied and applied to municipal solid wastes landfills [41]. Also this impact into science had reviewed [42] and its structure had analysed [43].

Some concepts of eco-efficiency had been applied to optimal performance evaluation of thermal cycles by [44] and to residential development at city level [45], where environmental impacts had been evaluated through carbon dioxide footprints evaluation.

The ecological efficiency levels of each type of power plant was considered in their works by [46,47], presenting the emissions of particulate material, sulphur dioxide ($SO_2$), carbon dioxide ($CO_2$) and nitrogen oxides ($NO_x$) emitted by power plants. Expanding this application, the evaluation and quantification of the environmental impact from the use of some renewable fuels and fossils fuels in internal combustion engines had been studied by [48].

Hence, in this work is presented the case that evaluates the possible economical and environmental gains with the application of water solar heating as an alternative for the consumption of natural gas in chemical reactors from cosmetic industries.

The proposal consists of pre-heating of water for a boiler producing steam to heat several reactors from an industrial unit and measure the impacts caused by this application.

Applying methods for identifying opportunities for optimisation of natural resources consumption, atmospheric emissions, and operational costs, this work has as its aim to study and to improve a process that consumes non-renewable natural resources (natural gas) and decreases greenhouse effect gases emission during its operations for steam production.

## 2. Methodology

The present work applies an analysis methodology based on thermoeconomic optimisation for a steam generation unit and production reactors heating in a chemical plant. According to [49–51], this methodology consists at first in identifying the system functions as a whole and then individually for each unit, creating the thermoeconomic functional diagram, formulating the cost problem and solving the mathematical equations associated to the system.

Also, greenhouse gases protocol [52–53] and ecological efficiency [54–56] are applied to the system in order to evaluate its impact into environment.

## 3. Results and discussion

The first step consists in identification of each unit component and its inputs and outputs as represented in Fig. 1 for heating process system on study.

The next step consists of a fundamental stage for developing the model: to create the thermoeconomic functional diagram. Fig. 2 shows the thermoeconomic functional diagram for the system on study.

### 3.1. Thermodynamic properties of steam production system

The consumption and operational data on several steps for the steam production system adopted in this study permits to assembly a table with thermodynamic properties as shown in Table 1. These properties are obtained by use of CATT2 software [57] and measurements directly from the process. After that, using the mathematical expressions related from Eqs. (1)–(21) and the thermodynamic properties from Table 1, it is possible to obtain the steam system exergetic flow values, shown in Table 2.

Unit 1: Softening

$$Y_{1,1} = \dot{m}_1 \times [(h_1 - h_0) - T_0 \times (s_1 - s_0)] \quad (1)$$

$$Y_{1.1} = \dot{m}_8 \times [(h_8 - h_1) - T_0 \times (s_8 - s_1)] \quad (2)$$

$$Y_{1.2} = \dot{m}_2 \times [(h_2 - h_1) - T_0 \times (s_2 - s_1)] \quad (3)$$

Unit 2: Boiler

$$Y_{2,1} = Y_{1.2} \quad (4)$$

$$Y_{2,2} = \dot{m}_{14} \times LHV_{ng} \quad (5)$$

$$Y_{2,3} = \dot{m}_9 \times cp_{air} \times \left[(T_9 - T_0) - T_0 \times \ln\left(\frac{T_9}{T_0}\right)\right] \quad (6)$$

$$Y_{2,4} = Y_{6.1} \quad (7)$$

$$Y_{2.1} = \dot{m}_{11} \times cp_{eg} \times \left[(T_{11} - T_0) - T_0 \times \ln\left(\frac{T_{11}}{T_0}\right)\right] \quad (8)$$

$$Y_{2.2} = \dot{m}_{10} \times [(h_{10} - h_2) - T_0 \times (s_{10} - s_2)] \quad (9)$$

$$Y_{2.3} = \dot{m}_3 \times [(h_3 - h_2) - T_0 \times (s_3 - s_2)] \quad (10)$$

Unit 3: Production reactors

$$Y_{3,1} = Y_{2.3} \quad (11)$$

$$Y_{3.1} = \dot{m}_4 \times [(h_4 - h_3) - T_0 \times (s_4 - s_3)] \quad (12)$$

Unit 4: Pump 1

$$Y_{4,1} = Y_{3.1} \quad (13)$$

$$Y_{4,2} = W_{B1} \quad (14)$$

$$Y_{4.1} = \dot{m}_5 \times [(h_5 - h_4) - T_0 \times (s_5 - s_4)] \quad (15)$$

Unit 5: Tank for condensing

$$Y_{5,1} = Y_{4.1} \quad (16)$$

$$Y_{5.1} = \dot{m}_6 \times [(h_6 - h_5) - T_0 \times (s_6 - s_5)] \quad (17)$$

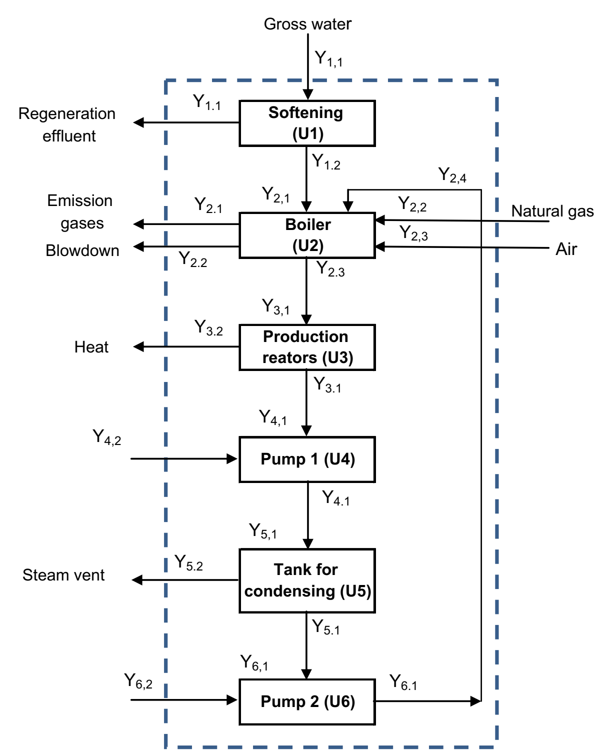


**Fig. 2.** Thermoeconomic functional diagram for steam production and heating reactors.

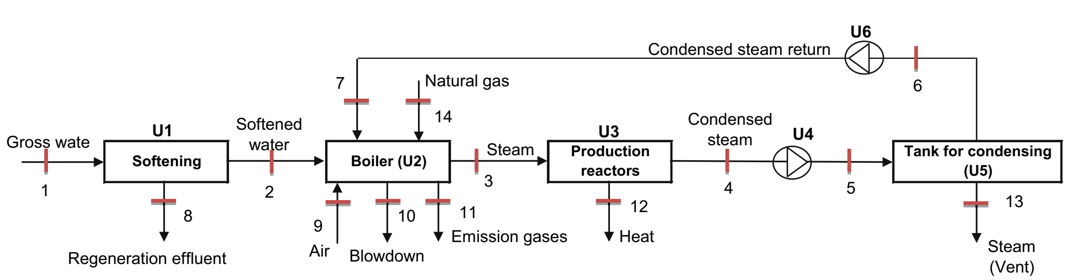


**Fig. 1.** Process diagram for steam production and heating reactors with identification of each unit and its inputs and outputs.

**Table 1**
Thermodynamic properties of the steam generation system.

| Point | Fluid | Flow (kg/s) | Pressure (MPa) | Temperature (K) | Specific enthalpy (kJ/kg) | Specific entropy (kJ/kg K) | Specific exergy (kJ/kg) |
|---|---|---|---|---|---|---|---|
| 0 | Water | – | 0.101 | 298.15 | 105 | 0.3673 | – |
| 1 | Gross water | 0.2911 | 0.3 | 298.15 | 105.1 | 0.3673 | – |
| 2 | Softened water | 0.2772 | 0.3 | 298.95 | 108.5 | 0.3785 | – |
| 3 | Steam | 0.8333 | 0.9 | 448.55 | 2,774 | 6.623 | – |
| 4 | Condensed steam | 0.8333 | 0.2 | 393.15 | 503.7 | 1.528 | – |
| 5 | Pumped condensed steam | 0.8333 | 0.3 | 393.15 | 503.8 | 1.527 | – |
| 6 | Pumped condensed steam | 0.8333 | 0.101 | 363.15 | 376.9 | 1.192 | – |
| 7 | Condensed steam | 0.5563 | 1.2 | 363.15 | 377.8 | 1.192 | – |
| 8 | Regeneration effluent | 0.0139 | 0.3 | 299.35 | 110.2 | 0.3841 | – |
| 9 | Air | 1.1568 | 0.005 | 303.15 | – | – | – |
| 10 | Blowdown | 0.0002 | 0.9 | 448.55 | 2,774 | 6.623 | – |
| 11 | Exhaustion gases | 0.9032 | 0.101 | 453.15 | – | – | 33.02 |
| 12 | Heat | – | – | – | – | – | – |
| 13 | Steam (vent) | 0.00001 | 0.101 | 378.15 | 2,666 | 7.383 | – |
| 14 | Natural gas | 0.0458 | 0.002 | 293.15 | – | – | 51,378 |
| 15[a] | Water-boiler feed | 0.8335 | – | 341.45 | 285.8 | 0.934 | – |

[a] Point 15 represents the combination of two other points (2 and 7) which feed the boiler with softened water and condensed water.

**Table 2**
Exergetic flows of the steam generation system.

| Unit 1: Softening | | | Unit 2: Boiler | | | Unit 3: Production reactors | | | Unit 4: Pump 1 | | | Unit 5: Tank for condensing | | | Unit 6: Pump 2 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Value | Un. | | Value | Un. | | Value | Un. | | Value | Un. | | Value | Un. | | Value | Un. |
| $Y_{1,1}$ | 0.0291 | kW | $Y_{2,1}$ | 0 | kW | $Y_{3,1}$ | 2,073 | kW | $Y_{4,1}$ | −626 | kW | $Y_{5,1}$ | 0.33 | kW | $Y_{6,1}$ | 58 | kW |
| $Y_{1.1}$ | 0.0013 | kW | $Y_{2,2}$ | 2,353 | kW | $Y_{3.1}$ | −626 | kW | $Y_{4,2}$ | 1.49 | kW | $Y_{5.1}$ | 58 | kW | $Y_{6,2}$ | 4.48 | kW |
| $Y_{1.2}$ | 0.0168 | kW | $Y_{2,3}$ | 0.05 | kW | | | | $Y_{4.1}$ | 0.33 | kW | $Y_{5.2}$ | 0.002 | kW | $Y_{6.1}$ | −23 | kW |
| | | | $Y_{2,4}$ | −23 | kW | | | | | | | | | | | | |
| | | | $Y_{2.1}$ | 30 | kW | | | | | | | | | | | | |
| | | | $Y_{2.2}$ | 0.16 | kW | | | | | | | | | | | | |
| | | | $Y_{2.3}$ | 2,073 | kW | | | | | | | | | | | | |

$$Y_{5.2} = \dot{m}_{13} \times [(h_{13} - h_5) - T_0 \times (s_{13} - s_5)] \tag{18}$$

Unit 6: Pump 2

$$Y_{6,1} = Y_{5.1} \tag{19}$$

$$Y_{6,2} = W_{B2} \tag{20}$$

$$Y_{6.1} = \dot{m}_7 \times [(h_7 - h_2) - T_0 \times (s_7 - s_2)] \tag{21}$$

In Table 2, the exergetic flows with negative values ($Y_{2,4}$, $Y_{3.1}$, $Y_{4.1}$, and $Y_{6.1}$) indicate that the exergy transfer occurs in the opposite direction of heat transfer [58,59], according to sign convention adopted in this work.

The costs of steam production system for heating into chemical reactors, named PVAR system, can be represented by diagram shown in Fig. 3.

The exergetic production cost (EPC) represents the amount of exergy that has been needed to produce the internal flows and products of a process [60]. In this case, it can be evaluated through addition of cost associated to products needs to transform softened water into steam, Eqs. (22)–(24).

$$EPC = c_s + c_{so} \tag{22}$$

$$c_{so} = \frac{I_{so} \times f}{H \times Y_{1.2}} + c_{OM_{so}} \tag{23}$$

$$c_s = \frac{I_{cb} \times f}{H \times Y_{2.3}} + c_{OM_{cb}} + Y_{ng} \times \frac{Y_{2,2}}{Y_{2.3}} \tag{24}$$

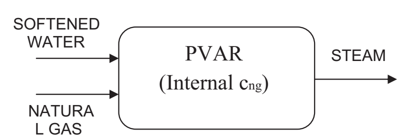


**Fig. 3.** Cost diagram of steam production system for chemical reactors heating (PVAR).

Commercial values for natural gas are presented out of SI system. So, they are used to evaluate an equivalent value for natural gas in exergetic cost (US$/kW h).

According to [61,62], it is possible to make an equivalence for natural gas cost in US$/kW h. Considering the CEG-Rio′s rate of 0.7512 US$/m$^3$, such as obtained on the August 1st, 2009 for industrial consumer from 10,001 to 50,000 m$^3$/month, the high heat value (HHV) of natural gas commercialized by this company is 9400 kcal/m$^3$ [63], and commercial dollar rating on the October 17th, 2009 [64], it is obtained Eq. (25) and the value of 0.0687 US$/kW h for the natural gas price.

$$c_{ng} = \frac{1.2998 \ \text{R\$/m}^3}{(9,400 \ \ kcal/m^3 \times 4.1868 \ \ kJ/kcal) \times \frac{1 \ \ h}{3600 \ \ s}} \times \frac{1}{1.7304 \ \ \text{R\$/US\$}} = 0.0687 \ \ \text{US\$/kW h} \tag{25}$$

Both Eqs. (26) and (27) are used to evaluate annuity factor for $k$=2, 4, 6, 8, 10 years and $r$=4, 8, 12, 16% per year.

$$f = \frac{q^k \times (q-1)}{(q^k - 1)} \tag{26}$$

where,

$$q = 1 + \frac{r}{100} \quad (27)$$

For the evaluation of costs associated to the steam production system, it has been estimated values for annual boiler operation and maintenance, and annual softening operation and maintenance, both shown respectively on Tables 3 and 4, besides other reference values for costs and investments are shown on Table 5.

Figs. 4 and 5 show the performance from values obtained for steam costs and water softening respectively.

These graphics make possible to note the PVAR system investment payback for each product associated. Fig. 6 shows the exergetic production cost for the system studied.

**Table 3**
Estimated values for annual boiler operation and maintenance.

| Item | Cost (US$) |
|---|---|
| **Work force for operation** | 83,218 |
| **Chemical treatment** | 24,272 |
| **Annual inspection** | 4,623 |
| **Spare parts** | 3,467 |
| **Total** | 115,580 |

**Table 4**
Estimated values for annual softening operation and maintenance.

| Item | Cost (US$) |
|---|---|
| **Work force for operation** | 16,644 |
| **Chemical products** | 5,201 |
| **Spare parts** | 2,167 |
| **Gross water** | 25,406 |
| **Total** | 49,418 |

**Table 5**
Reference values for PVAR system cost evaluation.

| Variable | Value |
|---|---|
| $H$ (h/year) | 8,200 |
| $c_{OMcb}$ (US$/kW h) | 0.0060 |
| $c_{ng}$ (US$/kW h) | 0.0687 |
| $c_{OMso}$ (US$/kW h) | 0.0026 |
| $I_{cb}$ (US$) | 69,348 |
| $I_{so}$ (US$) | 34,674 |
| $Q_{ng}$ ($m^3$/h) | 53.96 |
| $c_{so}$ (US$/$m^3$) | 5.1167 |

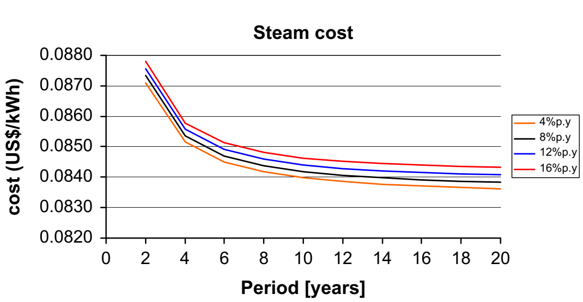


**Fig. 4.** Costs for PVAR system steam production.

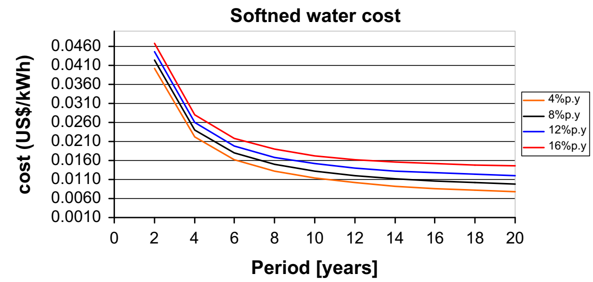


**Fig. 5.** Costs for PVAR system water softening.

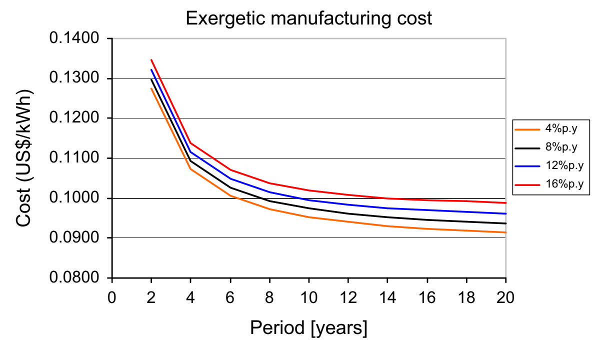


**Fig. 6.** PVAR system exergetic production cost.

### *3.2. Environmental impact associated to the steam production system*

The standard NBR ISO 14001:2004 [65] defines environmental aspect as

"the element of an organization's activities, products or services that can interact with the environment"

and environmental impact as

"any change to the environment, whether adverse or beneficial, wholly or partially resulting from an organization's environmental aspects".

Thus, based on the NBR ISO 14001 definitions [65], the major environmental aspects and impacts directly associated to the continuous operation of the steam production system on study are those related to inputs and outputs from this system, highlighting the following impacts at the input:

- The consumption of the renewable natural resource (water) due to the need of introducing a replacement chain for compensate the water wastes in the system, which environmental impact is the potential contribution to the lack of this renewable natural resource;
- The fossil fuel (natural gas) consumption for combustion, which environmental impact is the potential contribution to the lack of this non-renewable natural resource.

At the output the following impacts are highlighted:

- The generation of liquid effluent produced by the boiler blow down, which potential environmental impact is the possibility to change the water stream quality (the water quality of the stream that receives the treated waste water); and
- The atmospheric emission through boiler chimney, which is the result of natural gas combustion and potential environmental impact is the change on the air quality due to the dust

emission, sulphur dioxide ($SO_2$), and nitrogen oxides ($NO_x$), also its contribution to intensify the greenhouse effect due to the carbon dioxide ($CO_2$) emission.

Within this context, the present work is exclusively dedicated to the environmental aspects related to the natural gas consumption and, consequently, the $CO_2$ emission.

### 3.2.1. Estimate of greenhouse effect gases emission

The estimate of greenhouse effect gases emission in this case study depends basically on fossil fuel consumption. Starting from mass flow of 0.0458 kg/s mentioned on Table 1, the specific mass of natural gas (0.766 kg/N $m^3$) [66] and the number of hours in annual operation (Table 5), it is obtained the fuel annual consumption which will be used for the evaluation of the greenhouse effect gases, according to Eq. (28).

$$Q_{ng} = \frac{0.0458\ kg/s}{0.766\ \text{kg/N m}^3} \times \frac{3600\ s}{1\ h} \times \frac{8200\ h}{year} \times HHV_{ng} \tag{28}$$

According to [66], the higher heat value of natural gas is 9400 kcal/m³ (39,348,400 kJ/m³ or 10,932 kW h/m³), and from Eq. (28), it is obtained Eq. (29).

$$Q_{ng} = \frac{0.0458\ kg/s}{0.766\ \text{kg}/N\ \text{m}^3} \times \frac{3600\ s}{1\ h} \times \frac{8200\ h}{year} \times 10,932\ \text{kW}\ h/N\ \text{m}^3 = 19,295,351\ \text{kW h}\ year \tag{29}$$

Now, for an easy form to get a greenhouse gases emission estimate in line with what has been defined by the International Panel on Climate Change—Guideline for National Greenhouse Gas Inventories, it is available through The Greenhouse Gas Protocol Initiative Foundation, a protocol called GHG Protocol tool for stationary combustion, version 4.0 [52,53], which results in the values of Table 6 for the stationary steam combustion studied.

## 3.3. Proposal for the reduction of greenhouse effect gases emission

One goal of the present work is to evaluate the technical and economical viability in fostering the pre-heating in this steam production system by means of solar panels, promoting the increase of softened water temperature, which feeds the boiler through stream 2 in Fig. 1. However, before deepening into this possible alternative, it is indispensable to evaluate one of the streams with great potential for utilization: the gases emission through stream 11 in Fig. 1. The utilization of this potential heat produced by gases emission is commonly made by equipment named economizer.

### 3.3.1. Pre-heating with economizer for boilers

The economizers are gas-water type heat exchangers that are used to heat the feeding water before its introduction into the boiler. This pre-heating is made by the heat transfer between the combustion gases leaving the boiler and the feeding water as showed in Fig. 7.

In general, the economizers are made by winged tubes of carbon steel, stainless steel or cast iron. The water to be heated circulates inside tubes and the emission gases produced during the combustion circulate outside of them. According to the boilers manufacturer [67], the use of the economizer can generate a fuel consumption reduction of at least 5%.

### 3.3.2. Pre-heating with thermal solar energy

According to [68], although Brazil is the seventh largest solar collectors installed area in the world, with only 1.72 m² of installed collect area for each 100 thousand inhabitants, much less than Cyprus (84.4), Barbados (26.9) and Turkey (13.5). Additionally, annual average increase rate of collected area installed in Brazil is 14%, whereas in Canada it is 50%, in Germany, 39% and in France and Greece, 34%. Hence, due to the Brazilian's high potential solar energy there are many opportunities for the optimisation of electrical power and natural gas energy consumption, besides the supplying of remote areas.

Thus, the proposal of this work is to attach the solar heating for pre-heating of water. This one aims to take advantage from the available potential solar energy in Rio de Janeiro City that has an

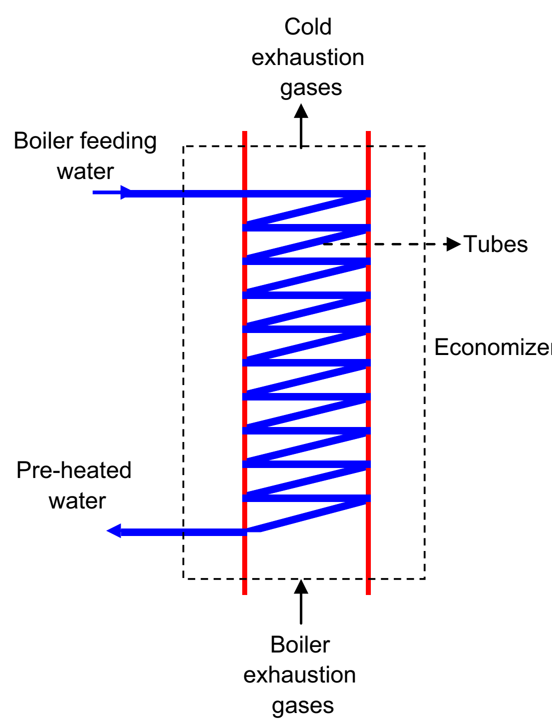


**Fig. 7.** Working features of boilers economizers.

**Table 6**
Total $CO_2$e emissions according to GHG Protocol tool for stationary combustion, version 4.0.

| User supplied data | | | | | | | GHG emissions (tonnes) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Source* ID | Sector | Fuel type (e.g., solid fossil) | Fuel | Amount of fuel | Units (e.g., kg or kW h) | Heating value basis | $CO_2$ | $CH_4$ | $N_2O$ | All GHGs (tonnes $CO_2$e) |
| 1 | Energy | Gaseous fossil | Natural gas | 19,295,351 | kW h | Lower | 3896.577 | $6.946 \times 10^{-2}$ | $6.946 \times 10^{-3}$ | 3900.384 |
| | | | | | | | Total GHG emissions from fossil fuels (tonnes $CO_2$e): | | | 3900.384 |
| | | | | | | | Total $CO_2$ emissions from biomass (tonnes) | | | 0.000 |

annual average of daily global solar radiation rating of approximately 16 MJ/m$^2$.day, according to [69]. This proposal consists basically of a facility to provide through forced circulation of water as showed in Fig. 8.

According to [70], a heating solar system is composed by a group of equipments, accessories, and its hydraulic connections that operates by natural or forced circulation. The forced circulation occurs due to a phenomenon called thermo-fission in which the fluid movement is produced by the difference of density induced by the temperature variation.

Fig. 8 shows a heating solar system with forced fluid circulation, a kind of process commonly used in industrial facilities and in which the circulation is forced by a pressure produced outside, generally by a pump. This configuration permits a flexible arrangement for the thermal reservoir.

This way, combining the utilization of the heat produced by available solar energy and by the gases emission sent to the atmosphere, this system presents the configuration showed in Fig. 9.

### 3.4. Expected reductions in costs and greenhouse gases emission

The greenhouse effect gases reduction estimation depends on the fossil fuels consumption reduction. To estimate these natural gas consumption reductions, two main data sources will be used:

- The boiler manufacturer [67] that appoints a minimum 5% economy in relation to boiler fuel consumption when an economizer is used; and
- CEPEL (Electrical Energy Research Centre), subordinate to the Brazilian Mines and Energy Ministry that by means of CRESESB (Wind and Solar Energy Reference Centre "Sergio Brito") that makes data available for cost and investment in thermal solar and photovoltaic systems.

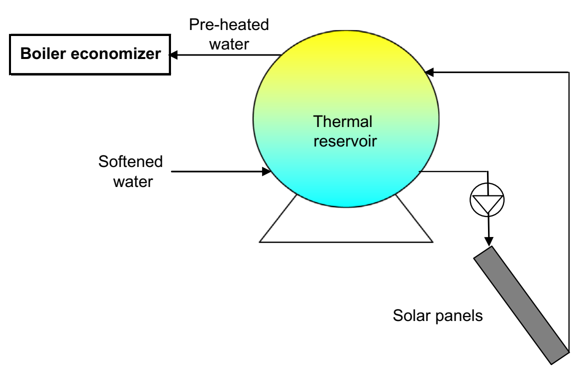


**Fig. 8.** Diagram of pre-heating solar system proposed.

To size up a thermal solar heating system, it is needed to take into account several variables, among them the daily solar average radiation, thermal yielding of the collector used, type and volume of thermal reservoir to be adopted, total area for collectors, heated water final temperature, and others. Hence, such dimensional evaluation must be the aim of a separate study. However, some data are indispensable for identification of essential values that contribute to the successfulness of this work.

The final temperature to be reached by the water is an indispensable variable to be defined.

According to [71], nowadays, the Brazilian market has available new appropriate collectors for industrial solar heating applications in a range between 80 °C and 250 °C. This study will adopt the minimum value of this range as maximum solar system temperature. Thus, using the data from Table 1 and Eq. (30), it is possible to estimate the amount of energy that will be necessary to get up the temperature from 25 °C to 80 °C.

$$Q = \dot{m} \times c_p \times (T_{out} - T_{in}) \tag{30}$$

where, $c_p = 4.18$ kJ/kg °C.

Then:

$$Q = 0.2772 \ \text{kg}/s \times 86,400 \ s \ day \times 4.18 \frac{\text{kJ}}{(kg \ ^oC)} \times (80-25 \ ^oC) = 5506,123 \ \text{kJ}/day$$

$$Q = 5506,123 \ \text{kJ}/day \times \frac{1 \ \ \text{kW h}}{3600 \ \ \text{kJ}} = 1529 \ kW \ h/day$$

Hence, considering 24 h of operation, the total power installed of the solar system is obtained through Eq. (31).

$$P = \frac{1529\text{kW h}}{24 \ \ \ \text{h}} = 63.7 \ kW \tag{31}$$

The evaluated data and the total of annual operation hours mentioned on Table 5, permits to estimate the annual reduction of natural gas energy consumption ($e_{\text{annual}}$) through Eq. (32).

$$e_{annual} = P \times H \tag{32}$$

$$e_{annual} = 63.7 \ kW \times 8200 \ h/year = 522,340 \ \text{kW} \ h/year$$

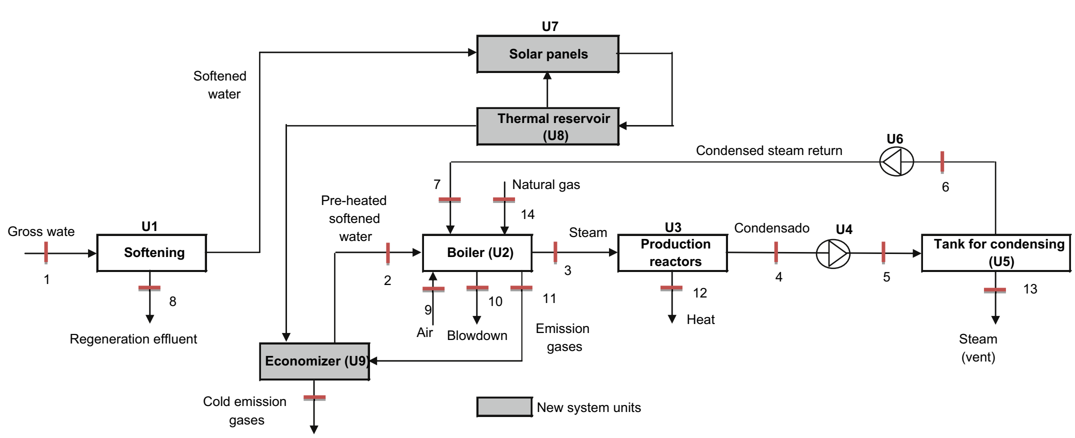


**Fig. 9.** Diagram of reactors steam heating production with the new unities proposed.

#### 3.4.1. Reduction of greenhouse gases emission

The results obtained with evaluations through Eqs. (33) and (34) are based in a situation named scenario 2, showed in Fig. 9, and now increased with:

- Solar heating system with an output temperature of 80 °C; and
- Economizer to use the thermal energy from boiler gases exhaustion for heating that permits a 5% energy consumption reduction.

Thus, the scenario 2 differs thermodynamically from the original scenario basically in relation to the stream 2 (softened water) mentioned in Fig. 9, which now has an input temperature of 80 °C, previously situated in about 25 °C.

The value $Q_{ng2}$ obtained through Eq. (33) indicates the natural gas consumption after the use of solar water heating system.

$$Q_{ng_2} = Q_{ng} - e_{annual} = 19,295,351\ \text{kW}\ h/year - 522,340\ \text{kW}\ h/year = 18,773,011\ \text{kW}\ h/year \quad (33)$$

The value $Q_{ng3}$ obtained through Eq. (34) indicates the natural gas consumption after the use of solar water heating system and an economizer that represents a minimal 5% fuel consumption, according to [67].

$$Q_{ng_3} = 18,773,011\ \text{kW}\ h/year \times 0.95 = 17,834,360\ \text{kW}\ h/year \quad (34)$$

Using the GHG Protocol tool for stationary combustion version 4.0 [52,53] for new conditions, the results showed in Table 7 are obtained.

Hence, according to results showed in Tables 6 and 7, the total greenhouse gases reduction in $tCO_2e$/year, it can be estimated through Eq. (35).

$$R_{CO_2e} = 3900.84\ tCO_2e - 3605.06\ tCO_2e = 295.78\ tCO_2e \quad (35)$$

#### 3.4.2. Cost reduction

In comparison with the initial conditions, the second scenario represents a situation with the same energy consumption but with a reduced natural gas consumption which makes possible a cost reduction of this fuel in US$/kW h due to the use of the heat available in solar energy and combustion gases. Thus, starting from Eq. (25), new consumption and cost values are obtained through Eqs. (36)–(39).

$$c_{annual-ng} = 19,295,351\ \text{kW}\ \text{h}/year \times 0.0687\ \text{US\$/kW h} = 1325,591\ \text{US\$/year} \quad (36)$$

$$e_{annual-ng} = 522,340\ \text{kW}\ h/year \times 0.0687\ \text{US\$/kW h} = 35,885\ \text{US\$/year} \quad (37)$$

$$c_{annual-ng_2} = 1325,591\ \text{US\$/year} - 35,885\ \text{US\$/year} = 1289,706\ \text{US\$/year} \quad (38)$$

$$c_{ng_2} = \frac{1289,706\ \text{US\$/year}}{19,295,351\ \text{kW}\ h/year} = 0.06684\ \text{US\$/kW h} \quad (39)$$

In Table 8 are showed the reference values used to evaluate the investment and in Tables 9–11 are values evaluated for scenario 2. To obtain easily a result for scenario 2, the economizer and solar system investment values were added in the variable $I_{cb}$, forming the $I_{cb2}$, mentioned in Table 11.

Figs. 10–12 shows the yield curves for values obtained for costs of steam, water softened, and exergetic production for the new system configuration (scenario 2).

Analysing graphics from Figs. 10–12, it is observed a clear similar tendency for the stabilization of cost of steam, softened water, and exergetic production what situates this stabilization in about eight years as the payback period. These graphics permit a comparison between initial situation and scenario 2 what is analysed in the sequence.

**Table 8**
Reference for cost and investment values in scenario 2.

| Variable | Reference value |
|---|---|
| **Installed power—solar energy [kW]** | 63.7 |
| **Investment—solar energy [US$/kW]** | 982.00 |
| **Total investment—solar energy [US$]** | 63,570.00 |
| **Investment—economizer [US$]** | 17,337.00 |
| **Spare parts annual cost** | 5% of investment |

**Table 9**
Estimated values for annual boiler operation and maintenance in scenario 2.

| Item | Cost (US$) |
|---|---|
| **Work force for operation** | 83,218.00 |
| **Chemical treatment** | 24,272.00 |
| **Annual inspection** | 4,623.00 |
| **Spare parts** | 7,513.00 |
| **Total** | 119,626.00 |

**Table 10**
Estimated values for annual softening operation and maintenance in scenario 2.

| Item | Cost (US$) |
|---|---|
| **Work force for operation** | 16,644.00 |
| **Chemical products** | 5,201.00 |
| **Spare parts** | 2,167.00 |
| **Gross water** | 25,406.00 |
| **Total** | 49,418.00 |

**Table 7**
Total $CO_2e$ emissions for scenario 2 according to GHG Protocol tool for stationary combustion, version 4.0.

| User supplied data | | | | | | | GHG emissions (tonnes) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Source ID | Sector | Fuel type (e.g., solid fossil) | Fuel | Amount of fuel | Units (e.g., kg or kW h) | Heating value basis | $CO_2$ | $CH_4$ | $N_2O$ | All GHGs (tonnes $CO_2e$) |
| 1 | Energy | Gaseous fossil | Natural gas | 17,834,360 | kW h | Lower | 3601.539 | $6.420 \times 10^{-2}$ | $6.420 \times 10^{-3}$ | 3605.057 |
| | | | | | | | Total GHG emissions from fossil fuels (tonnes $CO_2e$): | | | 3605.057 |
| | | | | | | | Total $CO_2$ emissions from biomass (tonnes): | | | 0.000 |

**Table 11**
Reference values for PVAR system cost calculation in scenario 2.

| Variable | Value |
|---|---|
| $H$ [h/year] | 8,200 |
| $c_{OMcb2}$ [US$/kW h] | 0.0061 |
| $c_{ng2}$ [US$/kW h] | 0.0675 |
| $c_{OMws2}$ [US$/kW h] | 0.0026 |
| $I_{cb2}$ [US$] | 127,138 |
| $I_{so2}$ [US$] | 34,674 |
| $Q_{ng2}$ [$m^3$/h] | 53.96 |
| $c_{so2}$ [US$/$m^3$] | 5.1167 |

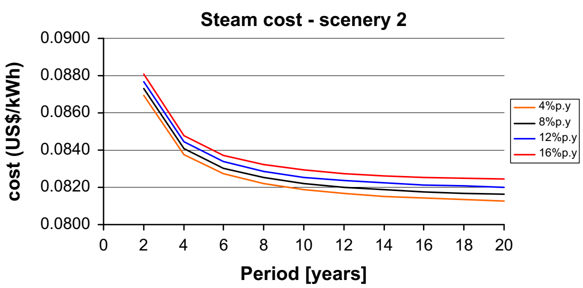


**Fig. 10.** Costs for PVAR system steam production in scenario 2.

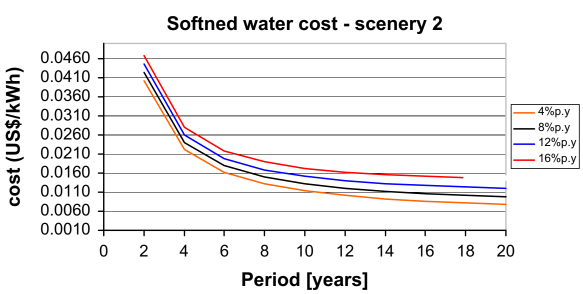


**Fig. 11.** Costs for PVAR system water softening in scenario 2.

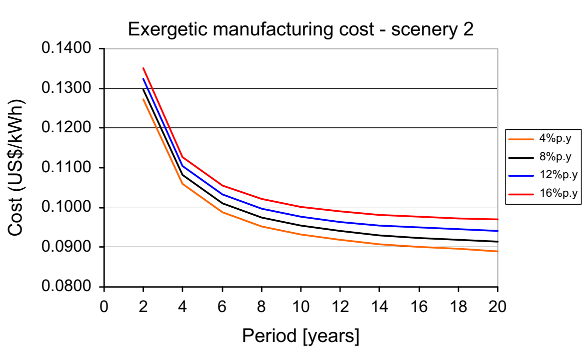


**Fig. 12.** PVAR system exergetic production cost in scenario 2.

### 3.5. Comparison between both sceneries and final considerations

As shown in Figs. 13 and 14, the comparison between the two sceneries demonstrates a cost reduction for steam production and exergetic production cost, in US$/kW h.

The system proposed to reduce the energy consumption does not interfere in the water softened system conditions. Thus, there is no interference in water softened costs, which is confirmed by the comparison between the results showed in Fig. 14.

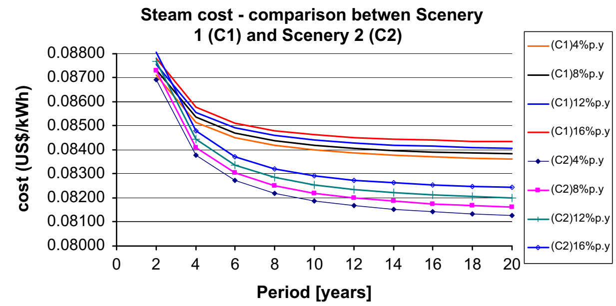


**Fig. 13.** Comparison between PVAR steam production costs in both sceneries.

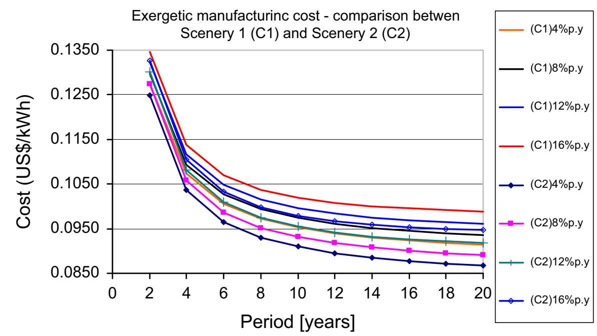


**Fig. 14.** Comparison between PVAR exergetic costs in both sceneries.

#### 3.5.1. A new analysis

Analysing the costs graphics from Figs. 13 and 14, it is observed a new clear similar tendency for the stabilization of costs of steam, softened water and exergetic production for both sceneries what situates this stabilization in about eight years as the payback period. However, considering that the system studied is operating and the investment is done, it is need to analyse the payback related with the investment to reduce the natural gas consumption.

Hence, employing the investment value for the economizer and thermal solar system (Table 9) and the annual cost reduction with natural gas, Eq. (37), it is obtained a payback based exclusively on the investments and costs related to the natural gas consumption reduction, as demonstrated through Eq. (40).

$$payback = \frac{81,000US\$}{35,885\,\frac{US\$}{year}} = 2.2\ \ years \tag{40}$$

It is highlighted here that for a total energy reduction consumption in 1,460,991 kW h/year, 295 $tCO_2e$/year and 35,885 US$/year, about 40% of the gains are promoted by solar heating and the remaining 60% are proportionate by the boiler economizer.

### 3.6. Ecological efficiency analysis

The ecological efficiency evaluates the pollutant amount of a system, considering gases emissions per kg of fuel used. This efficiency is ranged between 0 and 1; where an ecological efficiency equal to 0 means 100% of environmental impact, or high polluter, and an efficiency equal to 1 means 0% of environmental impact, or non-polluter.

Cardu and Baica [54,55] had introduced the concept of carbon dioxide equivalent [$(CO_2)_e$], based on maximum concentration allowed for $CO_2$, which is 10,000 mg/$m^3$. The equivalent coefficients for some pollutants, in kg per kg of fuel (kg/$kg_{fuel}$), called global warming potential (GWP), are related according to Eq. (41) [51,72–75]. These values consider a time horizon of 100 years for

these gases [76,77].

$$(CO_2)_e = CO_2 + 1.9 \times (CO) + 21 \times (CH_4) + 42.4 \times (H_2S) + 50 \times (NO_x) + 80 \times (SO_2) + 310 \times (N_2O) + 67 \times (PM) \tag{41}$$

An indicator is proposed by [54] to quantify environmental impact and it is defined as the difference between carbon dioxide equivalent of fuel and its low heat value. This indicator is called pollution indicator represented by $\Pi_g$, Eq. (42).

$$\Pi_g = \frac{(CO_2)_e}{LHV} \tag{42}$$

where:

$(CO_2)_e$ carbon dioxide equivalent ($kg/kg_{fuel}$);
LHV low heat value of fuel ($MJ/kg_{fuel}$);
$\Pi_g$ pollution indicator (kg/MJ).

Relating carbon dioxide emitted by fuel combustion process with its low heat value, Cardu and Baica [54] make possible comparison between different fuels. However a fuel can have a high low heat value and to emit a wide amount of pollutants into atmosphere or has negligible, or null, emissions of noxious gases, but cannot have the energy required to obtain a good efficiency in an industrial process.

Based on assumption that the best fuel is one that has the lowest pollution indicator, [54] propose a more complex and dimensionless index that expresses the ecological component of noxious gases emitted into atmosphere from the combustion of a fuel compared to useful energy produced in thermal power plants. The indicator proposed is called ecological efficiency ($\varepsilon$), such as Eq. (43).

$$\varepsilon = \left[\frac{0.204 \times \eta_{system}}{\eta_{system} + \Pi_g} \times \ln(135 - \Pi_g)\right]^{0.5} \tag{43}$$

According to [77,78], Brazil has the lowest average annual emissions of greenhouse gases, around 659 $kg_{CO_2}/t$, against world average around 800–880 $kg_{CO_2}/t$.

The ecological analysis is done through comparison between ecological efficiency, pollution indicator and values for $CO_2$ equivalent from cosmetic industry rate, before and after adoption of water solar pre-heating.

### 3.6.1. *Evaluation of ecological efficiency for cosmetic plant before solar water pre-heating*

For evaluation of cosmetic plant without solar water pre-heating practice are considered, a low heat value of 38,348.4 kJ/kg for natural gas [66], a steam production of 24,599.016 t/year and a fuel consumption of 1352.016 toe/year, resulting a global efficiency ($\eta_{system}$) as 2. Table 12 shows global warming potential values for the case study plant before solar water pre-heating policy adoption.

**Table 12**
GWP values for the case study plant before solar water pre-heating.

| | GWP (kg/kg fuel) |
|---|---|
| **$CO_2$** | 1,846.2837 |
| **CO** | 0.0015025 |
| **$H_2S$** | 0.0000376 |
| **$NO_x$** | 3.9264597 |
| **$SO_2$** | 0.12857 |
| **PM** | 0.073139936 |

**Table 13**
GWP values for the case study plant with solar water pre-heating.

| | GWP (kg/kg fuel) |
|---|---|
| **$CO_2$** | 1773.7224 |
| **CO** | 0.0014434 |
| **$H_2S$** | 0.0000361 |
| **$NO_x$** | 3.7721447 |
| **$SO_2$** | 0.12352 |
| **PM** | 0.070265441 |

Carbon dioxide equivalent for facility on study is obtained applying values from Table 12 to Eq. (41).

$$(CO_2)_e = 2057.797 \left[\frac{kg}{kg_{fuel}}\right]$$

Actually, the most common fuel in cosmetic industry is natural gas, then following evaluations are based on it.

$$\Pi_g = 53.660 \left[\frac{MJ}{kg}\right]$$

$$\varepsilon = 0.016$$

### 3.6.2. *Evaluation of ecological efficiency for cosmetic plant after solar water pre-heating*

For evaluation of actual cosmetic plant with solar water pre-heating practice are considered a lower heating value of 38,348.4 kJ/kg for natural gas [66], a steam production of 24,599.016 t/year and a fuel consumption of 1,298.88 toe/year, resulting a global efficiency ($\eta_{system}$) as 2. Table 13 shows global warming potential values for the case study plant after solar water pre-heating policy adoption.

Carbon dioxide equivalent for new configuration of facility on study is obtained applying values from Table 13 to Eq. (41).

$$(CO_2)_e = 1976.923 \left[\frac{kg}{kg_{fuel}}\right]$$

Such as the previous scenario, natural gas was considered as main fuel, but its consumption is less than the first case because the introduction of solar water pre-heating.

$$\Pi_g = 51.551 \left[\frac{MJ}{kg}\right]$$

$$\varepsilon = 0.017$$

## 4. Conclusions

Based on the investment demands, expected results for fossil fuel consumption reduction and a consequently beneficial impact on the amount of greenhouse effect gases emission and a payback of approximately two years, this solution in study might be consider attractive.

The present study permits now to access a methodology to evaluate the several conditions for operation and costs for this system. Additionally, the applied method demonstrated that the utilization of energy available in solar energy radiation and boiler gases exhaustion can contribute to reduce greenhouse effect gases and energy consumption in approximately 8%. Such reduction will permits a two years investment recover, excluding the possible gains with carbon credits market due to annual reduction of approximately 300 $tCO_2e$ what can promote at least a reduction in the estimated payback.

Hence, the main conclusion is that the present work contributes to the economical and environmental viability analysis to use in industrial processes an energy source highly available, especially in Brazil, and in the industrial plant studied, contributing with the studies for alternatives sources for optimisation use of a fossil fuel strongly preset in the Brazilian energy matrix.

Despite the reduction of $CO_2$e emissions in tonnes of $CO_2$e, applying ecologic efficiency analysis methodology to this system is clear that it continues very pollutant. Thus, it should be important to invest not only in solar water pre-heating system, but also into technologies to mitigate these greenhouse gases, such as selective catalytic reduction (SCR) that reduces $NO_x$ around 85%; flue gas desulfurization (FGD) that reduces $SO_2$ around 90%; electrostatic precipitator (ESP), or electrostatic air cleaner, that reduces MP around 99.2%; and others.

These technologies associated to alternative energy sources use in replacement of natural gas can provide a better ecologic efficiency value for this system.

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